Effects of the Elwha River Dam Removal Project on Suspended-Sediment Concentrations in the River and Nearshore Environment

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Abstract

Suspended-sediment concentrations (SSCs) in the Elwha River and nearshore environment off the river mouth were observed in order to determine the effects of the Elwha dam removal project on sediment supply to the river and marine environment. River gauge data over a 4-month period of dam removal from November 2011 to March 2012 was analyzed to identify deconstruction-caused SSC increases. Nearshore SSC was measured over the same period and was compared to oceanic and river data to determine controls on nearshore SSC levels. The 2011-2012 data was compared to data from a 2008 study to see what effects dam removal has had on SSC levels. The river had a background SSC level of about 100 mg L^{-1} with a maximum observed concentration of 2610 mg L^{-1}. Nearshore SSC had a background level of 0-20 mg L^{-1} during the study with periodic events reaching levels of 50 mg L^{-1} and a maximum of 121 mg L^{-1} on March 30. The highest recorded river SSC levels corresponded with major deconstruction events, while the highest recorded nearshore SSC levels corresponded with strong sediment input from the river. Comparison with the 2008 data was made difficult by the large difference in river discharge between the two study periods. Dam removal resulted in pulses of sediment to the river that were measurable off the mouth of the river, indicating that deconstruction had a direct on effect on SSCs in both the river and nearshore environment.

1. Introduction

Small mountainous rivers are a significant source of sediment flux to the ocean (Milliman and Syvitski, 1992). Sediment supplied to the ocean by rivers can accumulate locally or be transported along or across the continental shelf and contribute to geological processes elsewhere (Nittrouer and Wright, 1994). Many studies have looked at the effects of natural and anthropogenic processes on suspended-sediment concentrations (SSCs) in rivers (Lopez-Tarazon et al., 2010; Nu-Fang et al., 2011; Gao and Josefson, 2012), but the effects of increased sediment supply on nearshore SSC are less well known. Two dams on the Elwha River have blocked most of the river's sediment transport for the last century. Removal of the dams began in September 2011, increasing sediment supply to the lower river and nearshore environment. This paper observes SSC in the river and off the mouth of the Elwha River during a 4-month period during initial dam removal and makes comparisons to river discharge, tide, wave data, and dam deconstruction milestones. Relationships between SSC and these processes are established to determine the dominant effects on SSC during the intermediate period between dam-limited sediment transport and a natural sediment supply to the lower river and nearshore environment.

2. Background

2.1. Regional setting

The Elwha River is a small mountainous river on Washington State’s Olympic Peninsula. Upstream of two hydroelectric dams the river is largely unimpacted by human activity, with 85% of the Elwha basin protected in Olympic National Park. Average annual precipitation varies with elevation: the area around the mouth receives 100 cm yr-1 of precipitation while heavy snowfall in the Olympic Mountains results in up to 500 cm yr-1 of precipitation at higher elevations (Philips and Donaldson, 1972). This precipitation results in a bimodal annual discharge pattern that peaks during the winter storms of December and January, and again during late-May and early-June snowmelt

(USGS gauge 12045500; waterdata.usgs.gov/WA/nwis/). The Elwha River drains into the Strait of Juan de Fuca. Flow in the Strait is characterized by strong tidal currents and swells generated in the Pacific Ocean.

The Elwha and Glines Canyon dams, completed in 1913 and 1917, respectively, have blocked all fish passage to the upper river and prevented much of the river's sediment transport, trapping 19x106 m3 of sediment in the reservoirs behind the dams (Bountry et al., 2010). Reduction of sediment supply to the nearshore environment off the mouth of the Elwha has resulted in erosion of the subaerial delta and Ediz Hook, the spit sheltering Port Angeles (Duda et al., 2011). In 1992 Congress passed the Elwha River Ecosystem and Fisheries Restoration Act, allocating funds to purchase the dams and develop a plan for removal, which began in September 2011. After dam removal it is expected that 7-8x106 m3 of trapped sediment will be eroded and transported downstream, thus greatly increasing sediment supply to the lower river and nearshore Strait of Juan de Fuca (Czuba et al. 2011).

2.2. Topical background

Nearshore SSCs off of river mouths are affected by several processes. Fluvial sediment supply to the ocean is determined by the amount of sediment transported by the river and how much escapes the estuary (Milliman and Syvitski, 1992). Unfilled estuaries trap much of the transported sediment before it reaches the ocean, while filled estuaries often result in sediment being transported out of the estuary in buoyant plumes, seen in the Elwha's predominantly eastward plume (Officer 1981; Warrick and Stevens, 2011). Sediment deposition and accumulation depend on the settling velocity of the particles and energy of the ocean environment; sediment advected to the ocean via buoyant plumes is initially deposited when the plume mixes with seawater, reducing the strong density gradient at the plume-seawater interface and allowing sediment to settle out. If the velocity of the tidal currents and strength of the waves are high enough at this initial deposition site the sediment can be resuspended and transported before finally accumulating elsewhere (Wright and Nittrouer, 1995). Nearshore SSC therefore results from two sources, advected and resuspended sediment.

3. Methods

3.1. Field data

Sensors mounted on an instrumented tripod located on the seafloor off the mouth of the Elwha River (Fig. 1) measured and logged data hourly during a deployment from November 29, 2011 through April 5, 2012. Nearshore SSC was measured with an optical backscatter sensor (OBS). Current velocities at the tripod were obtained with an Ocean Probe acoustic Doppler velocimeter. Significant wave height was measured with an acoustic Doppler current profiler (ADCP) sampling at 600 kHz. To evaluate the input of sediment to the nearshore environment surface water samples were collected from the Elwha River bridge upstream from the diversion structure (Fig. 1).

3.2. River and marine data

River data was supplied by USGS river gauges on the Elwha River (waterdata.usgs.gov/WA/nwis). River discharge was obtained from USGS gauge 12045500, and river turbidity data was taken from USGS gauge 12046260. Tide data was taken from the Port Angeles tide station (NOAA Station 9444090; tidesandcurrents.noaa.gov). All data were collected for the dates of the tripod deployment.

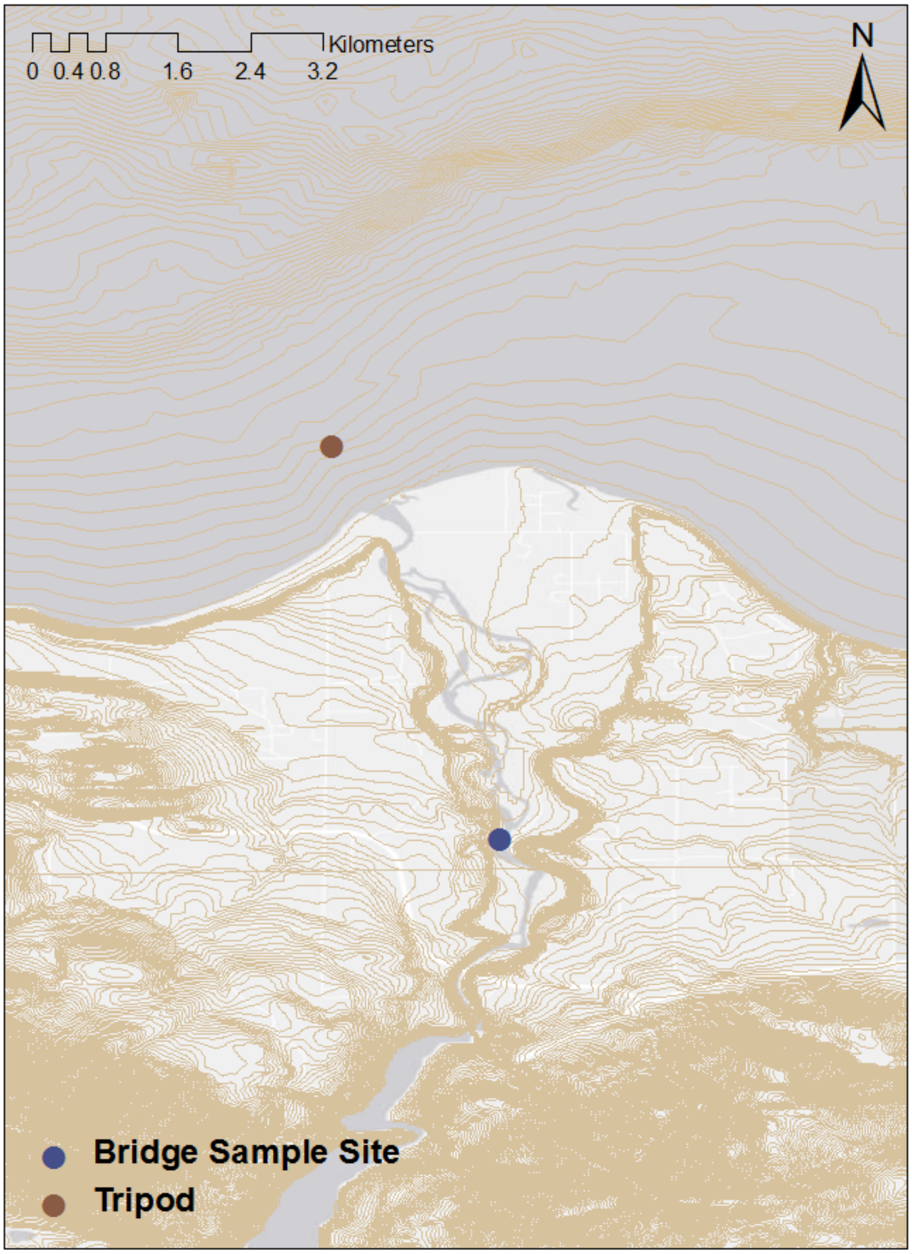

Figure 1. The Elwha River delta with the location of the tripod and the site where river samples were collected (Bathymetry DEM from USGS).

3.3. Data analysis

The water samples from near the diversion structure were filtered on weighed filters and dried overnight in an oven. The filters were weighed to determine SSC for each sample. These concentrations were compared to simultaneous turbidity measurements at the diversion structure gauge which measures in formazin nephelometric units (FNU) to construct a correlation curve to convert FNU to units of mg L^{-1}.

Increases in river discharge and significant wave height were identified as events. SSCs at the tripod were examined during each event to determine the relationships between the events and nearshore SSCs.

4. Results

4.1. River gauge calibration and discharge

Samples taken near the Elwha River diversion structure were filtered to determine SSC. These concentrations were plotted against concurrent turbidity readings from USGS gauge 12046260 (Fig. 2) to determine the relationship between turbidity and concentration, which was found to be:

$$C = 1.91 \times T - 30.9$$

where *C* is SSC in mg L^{-1} and T is turbidity in FNU. Applying this relationship to the river turbidity data resulted in a time series of SSC at the diversion structure (Fig. 3A) and allowed comparisons to nearshore SSC, also in mg L^{-1}. In the river, background SSC during the study period was 100-300 mg L^{-1}. Prior to mid-March, multiple river suspended-sediment events had maximum concentrations of 500-700 mg L^{-1}, while several events around January 1 had SSC levels that reached concentrations of >1000 mg

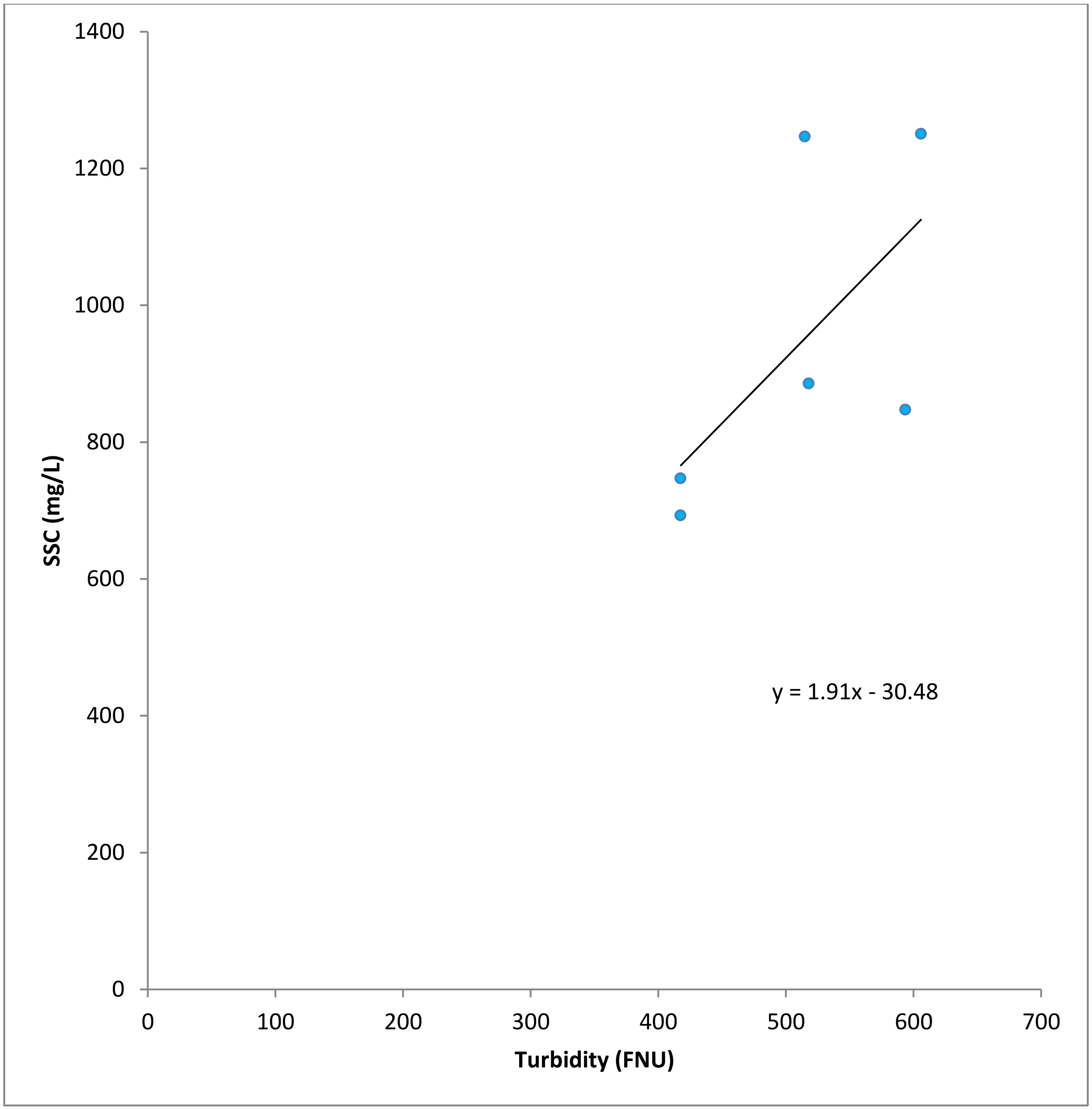

Figure 2. The relationship between Elwha River turbidity measurements in FNU at the diversion structure and SSC (mg L^{-1}) from bottle samples.

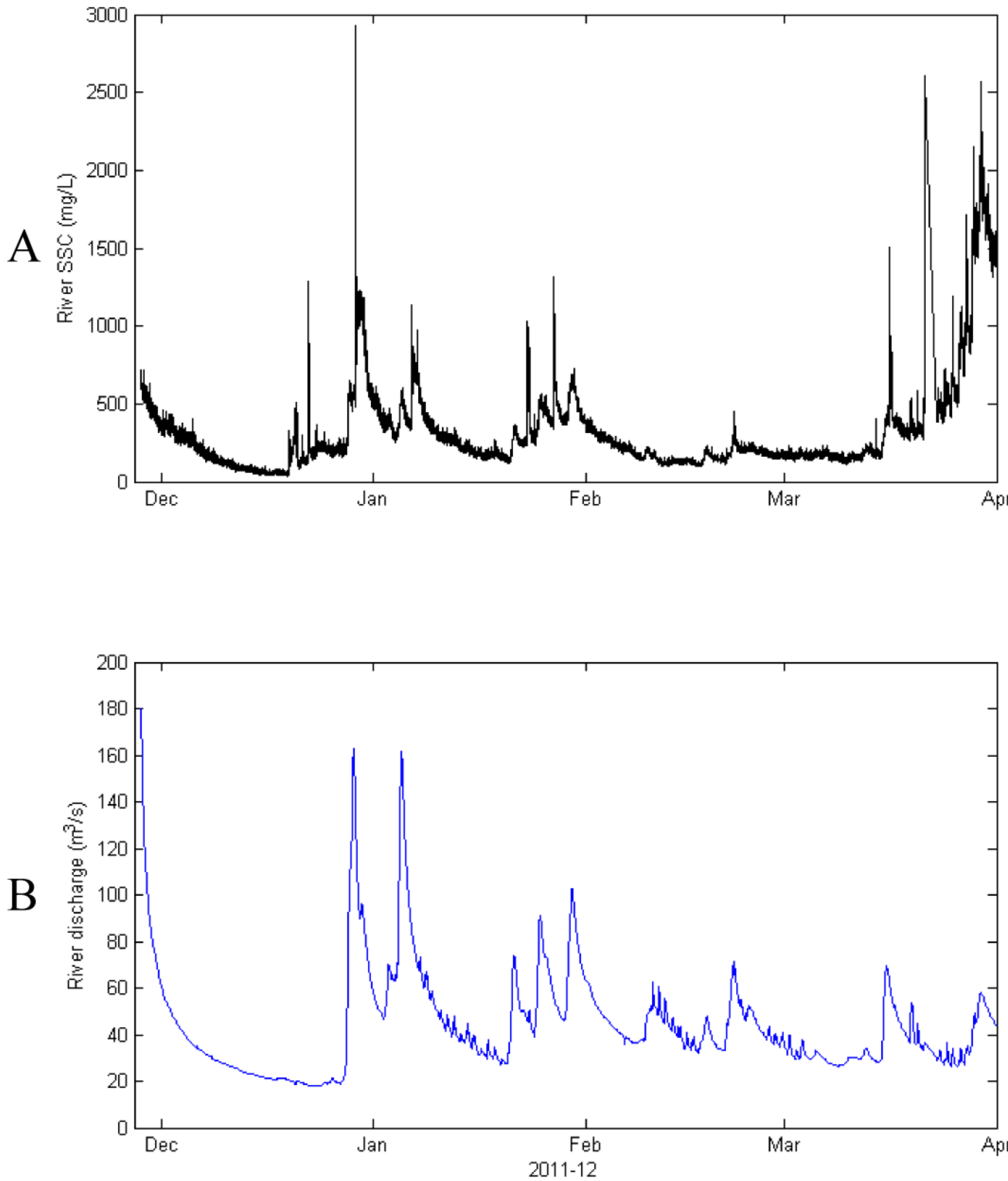

Figure 3. Calculated SSC of the Elwha River at the diversion structure over the 4-month study (A) and river discharge over the same period (B).

L^{-1}. The largest SSC observed during the study period occurred during a large event beginning in the middle of March, with a maximum SSC of 2600 mg L^{-1}.

River discharge peaked sharply during flood events and then gradually returned to the study period base flow (Fig 3B). Base flow was 25-40 $m^3 s^{-1}$. Floods on November 28, December 28, and January 6 each had peak discharges over 150 $m^3 s^{-1}$, with a maximum discharge of 180 $m^3 s^{-1}$ during the November flood. Multiple smaller floods during the record peaked at 50-100 $m^3 s^{-1}$.

4.2. Delta physical processes

Nearshore SSC varied over the deployment with a background level of 0-20 mg L^{-1} at the study site (Fig. 4A). SSC events occurred episodically and SSC levels typically reached 50 mg L^{-1}. One event on March 30 had a maximum SSC of 121 mg L^{-1}. Large, short-duration spikes apparent in the time series were attributed to organic activity or other interference, and were not evaluated in this study.

Significant wave heights (Hs) at the study site cycled between 0.1 m and 1 m throughout December and January (Fig. 4B). Starting in the middle of February, and continuing through March, wave strength increased, with Hs values reaching 1.5-2 m and a maximum of 2.3 m on February 25.

Tides in the study area were characterized by a mixed semi-diurnal pattern with large variations between spring and neap tides (Fig. 4C). The maximum tidal range during the study period was 3.50 m and the minimum range was 1.04 m. Near-bottom currents followed a similar pattern, increasing in speed as tidal range increased (Fig. 4D). The maximum recorded near-bottom current speed was 79.2 cm s^{-1}, and the mean current speed for the study period was 25.1 cm s^{-1}.

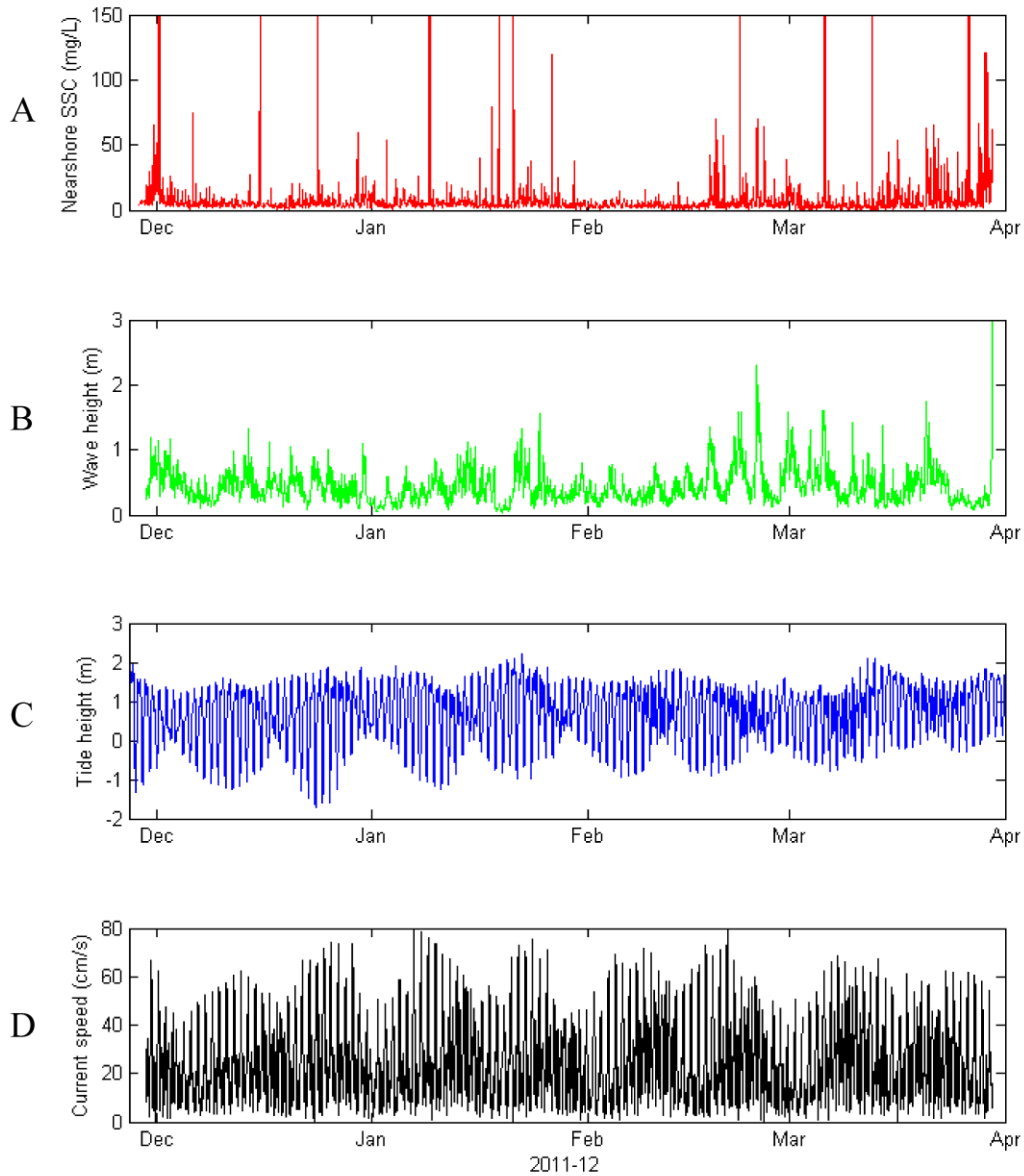

Figure 4. The SSC (A), significant wave height (B), tide height (C), and near-bottom current speed (D) at the study site off the mouth of the Elwha River.

5. Discussion

5.1. River SSC and discharge

Increased river discharge resulted in higher SSC levels in the river during the study period, but other increases in SSC were not caused by flood events. Of 18 identified SSC events (Fig. 5A), 11 were concurrent with flooding (Fig. 5B). Maximum SSC levels during the flood events ranged from 219-722 mg L^{-1}, averaging 485 mg L^{-1} (Table 1). SSC event A18 had a maximum concentration of 2570 mg L^{-1}, a much higher concentration than other flood events, but it was part of a longer-term event than the floods. The sediment spikes that did not result from increased discharge all coincided with major deconstruction events on the Elwha Dam (nps.gov/olym/naturescience/damremovalblog.htm). Drawing down Lake Aldwell and switching the river back into its natural channel at the Elwha Dam preceded large SSC events that saw SSC levels averaging 1290 mg L^{-1} with a maximum concentration of 2610 mg L^{-1} (Table 2).

The effects of river discharge on SSC agreed with other studies of small mountainous rivers, where discharge was the main factor in SSC levels (Lopez-Tarazon et al., 2010; Nu-Fang et al., 2011). Most of the sediment transport and the highest sediment concentrations after dam removal are expected three to five years after the dams are dismantled (Randle et al., 1996), implying that SSC levels in upcoming years could be higher than the levels observed during deconstruction events. These observations illustrate the immediate effects of dam removal on river systems.

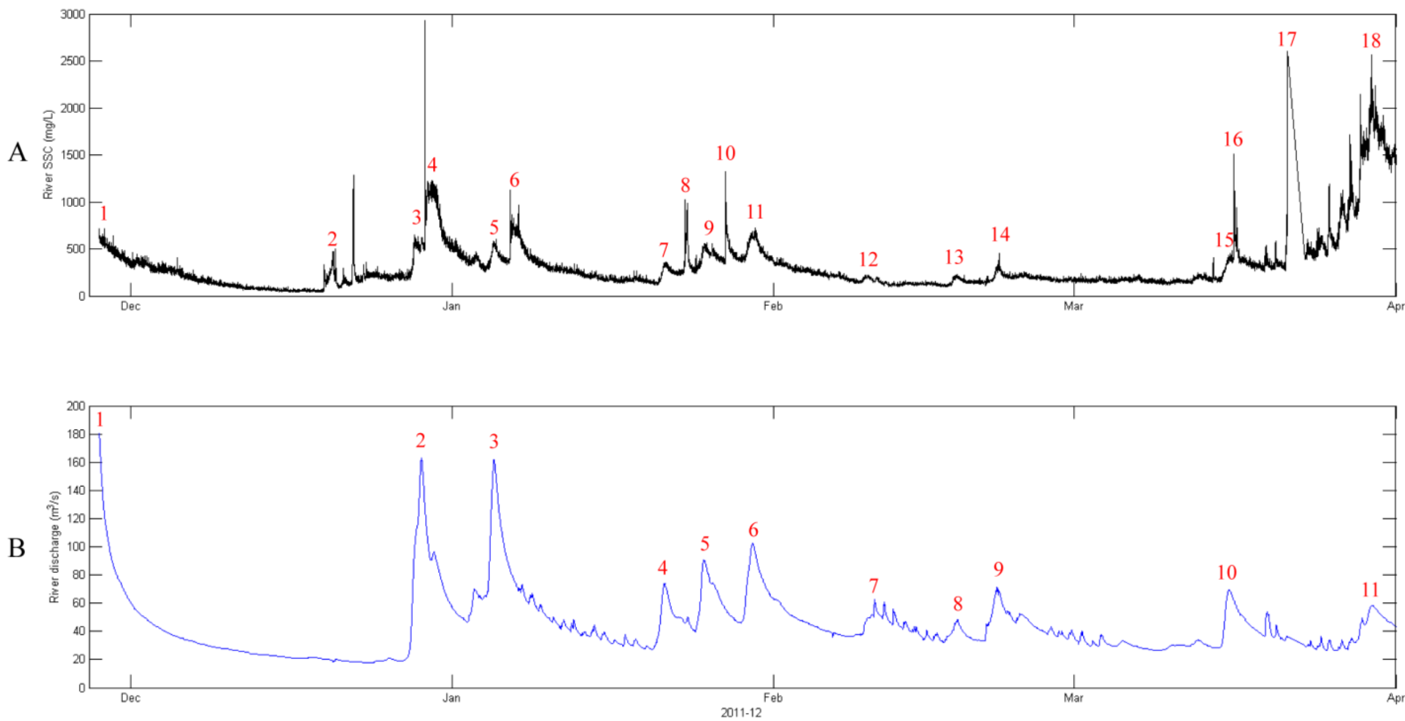

Figure 5. The SSC at the Elwha River diversion structure with SSC events identified and numbered (A) and Elwha River discharge with discharge events identified and numbered (B).

Table 1. River SSC events and corresponding floods on the Elwha River.

Date	River SSC Event (Fig. 5)	Maximum SSC (mg L^{-1})	Discharge Event (Fig. 5)	Maximum Discharge(m^3 s^{-1})
11/28/2011	A1	714	B1	180
12/29/2011	A3	651	B2	163
1/5/2012	A5	599	B3	162
1/21/2012	A7	364	B4	73.9
1/25/2012	A9	565	B5	90.9
1/30/2012	A11	722	B6	102
2/10/2012	A12	219	B7	62.6
2/18/2012	A13	233	B8	48.1
2/22/2012	A14	336	B9	71.4
3/15/2012	A15	456	B10	69.4
3/29/2012	A18	2570	B11	58.0

Table 2. River SSC events and corresponding Elwha Dam removal milestones.

Date	River SSC Event (Fig. 5)	Maximum SSC (mg L^{-1})	Major Deconstruction Event
12/20/2011	A2	504	River flow moved into its natural channel at the Elwha Dam
12/30/2011	A4	1230	River flow switched back into its natural channel at the Elwha Dam
1/6/2012	A6	869	Period of Lake Aldwell drawdown
1/23/2012	A8	989	River flow switched back into its natural channel at the Elwha Dam and Lake Aldwell drawn down 1 m
1/27/2012	A10	1320	Lake Aldwell drawn down 1 m
3/16/2012	A16	1510	River flow switched into natural channel for the final time, final Lake Aldwell drawdown begun
3/21/2012	A17	2610	Final Lake Aldwell drawdown continued

5.2. Controls on nearshore SSC

Waves and sediment supply from the river both affected nearshore SSC during the study period. Nearshore SSC events 1-4, 6, and 7 occurred during periods of high river SSC and strong waves (Fig. 6). The strongest waves recorded during the study period happened in the second half of February. Wave heights during these weeks reached 1.5 m and higher and coincided with the long-duration SSC event 5, without any significant sediment input from the river. There were no strong waves during event 8, but there was an extended period of high sediment concentration levels in the river. Small fluctuations consistent with the tidal cycle occurred throughout the study but didn’t change significantly with tidal range.

The nearshore SSC response to river sediment input and wave action indicates two possible processes. Most of the nearshore SSC events occurred during periods of both strong waves and high river sediment supply, making it difficult to distinguish which was the dominant process in raising SSC levels. However, SSC event 5 was solely wave-driven, while SSC event 8 was solely river-driven. This implies that sediment is being deposited on the delta and then being resuspended by wave action, two of the stages of river sediment dispersal outlined by Wright and Nittrouer (1995). As the dam removal process continues and more sediment is eroded from the former reservoirs and transported down the river, more sediment may be resuspended and dispersed across the delta, resulting in finer substrate compositions.

5.3. Comparison to 2008 data

Background SSC levels during the 2011-12 study were higher than during the 2008 study (Fig. 7), and the larger amount of sediment in the 2011-12 study fluctuated

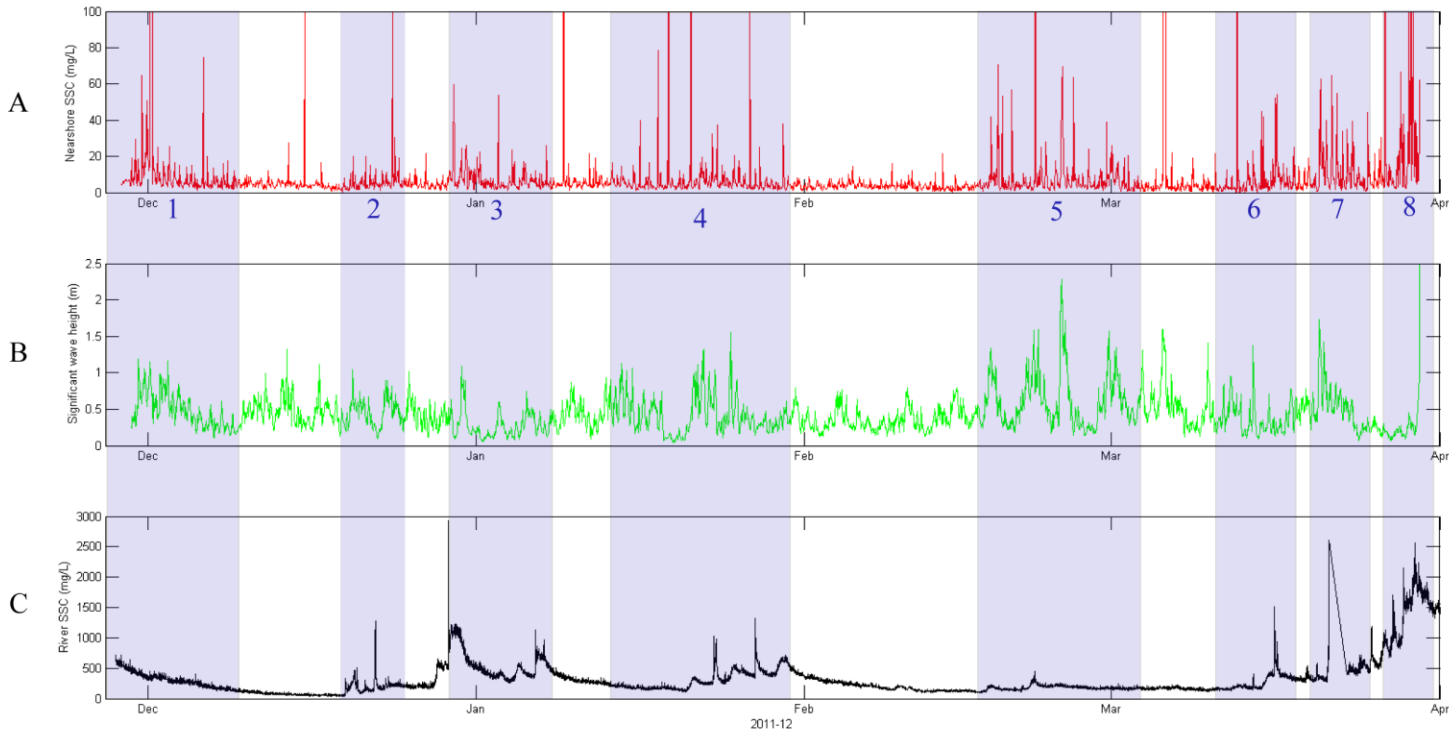

Figure 6. Nearshore SSC (A) and wave height (B) at the study site and SSC of the Elwha River (C). Nearshore SSC events are outlined in blue and numbered.

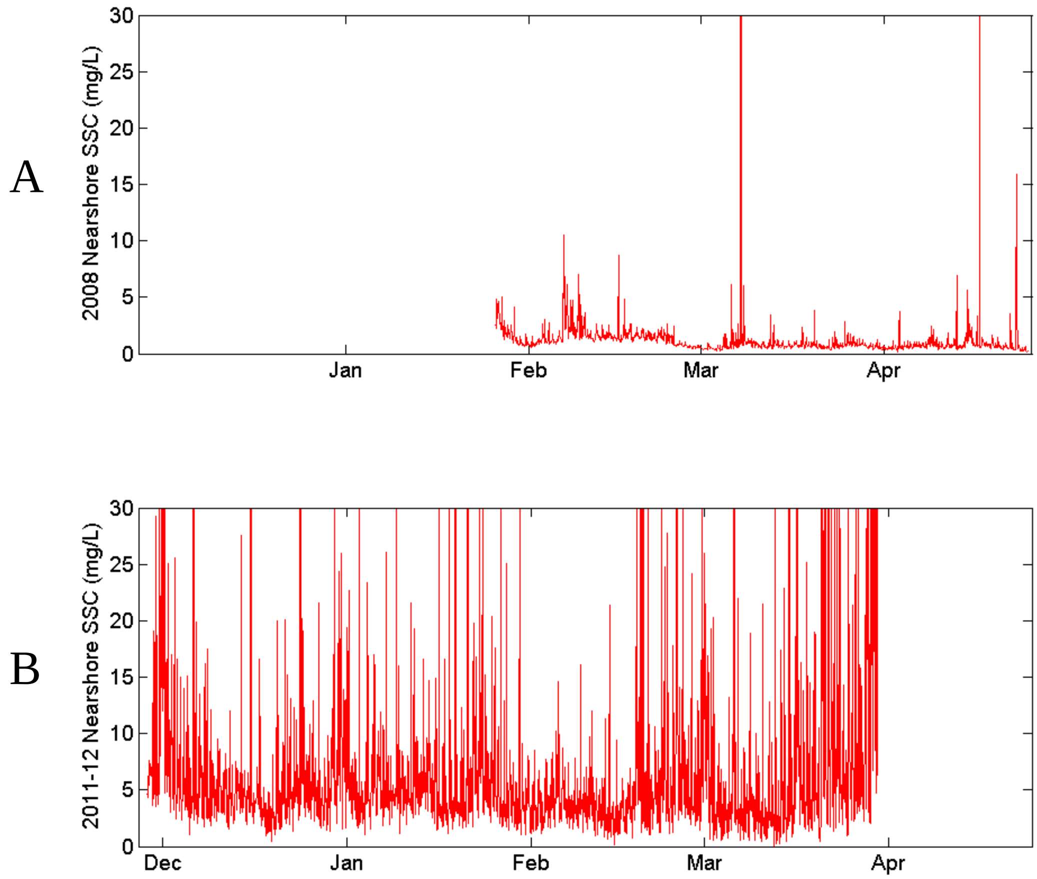

Figure 7. Nearshore SSC at the tripod site off the mouth of the river during the 2008 deployment (A) and the 2011-12 deployment (B) plotted on the same scale.

more with wave and tidal influence. While the higher nearshore SSCs observed in the more recent study are most likely due to increased sediment transport by the river, dam removal is not the only factor affecting suspended sediment in the river. River discharge was below average during the 2008 study, without any major floods and river discharge never >50 $m^3 s^{-1}$(Fig. 8A). For most of the 2011-12 study river discharge was above average, with several large floods of discharge >160 $m^3 s^{-1}$ (Fig. 8B). The river turbidity gauge was not installed until 2011, but the close relationship between discharge and river implies that much less sediment was transported down the river during the 2008 study.

This difference in river discharge makes it difficult to draw any meaningful conclusions about the dam removal's effects on nearshore SSC. Nearshore SSC event 8, which reached a maximum SSC of 121 mg L^{-1} (Fig. 6) was the most obvious example of the dam removal's influence. The drawdown of Lake Aldwell released a large pulse of sediment into the river that was measured by the OBS at the tripod site, indicating a direct effect of dam removal on nearshore SSC. Temporary peaks in future river SSCs are expected to exceed 30,000 mg L^{-1} (Randle et al., 1996), much higher than the maximum river SSC of 2610 mg L^{-1} observed during nearshore SSC event 8, implying that if those higher river SSCs are reached the nearshore environment will be affected more dramatically.

6. Conclusion

This study of river and nearshore SSCs found that they were influenced by the dam removal process. Deconstruction events have resulted in pulses of sediment into the river that increased river and nearshore SSCs. As the SSC of the river increased more sediment was supplied to the nearshore environment, increasing marine SSCs, and that

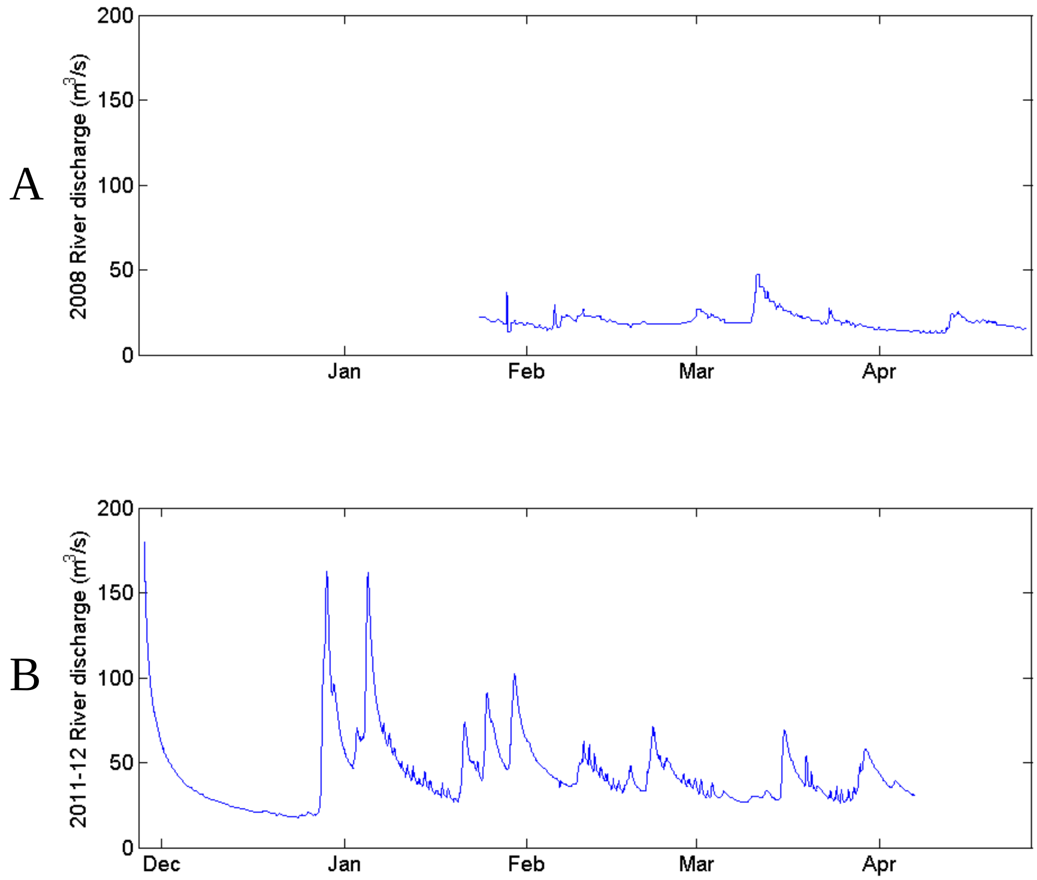

Figure 8. Elwha River discharge during the 2008 study (A) and the 2011-12 study (B).

sediment was more readily resuspended by strong waves. Nearshore SSCs were higher during the 2011-12 study than the 2008 study, but comparison between the two records is confounded by the significantly smaller river discharge in 2008.

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